Cover page

Title: Prognostic System for MicroStructural-Based Reliability

Authors: Loren Nasser
Robert Tryon

ABSTRACT

This paper overviews the work undertaken to date on development of a patent-pending material, microstructural-based structural prognosis system[1]. System development is currently underway and prognosis results, for OEM turbine disk component specimens, will soon be compared to fatigue test results.

Onboard prognosis technology will dramatically improve the conventional approach to system maintenance. Transitioning from fleet to condition-based maintenance strategies for air or land vehicles, infrastructure and electronics will save government and industry millions or even billions of dollars annually.

Real world variability influences why two nearly identical systems fail differently or at different times. The material behavior itself is a significant contributor to system variability – which is not explicitly considered by conventionally used life prediction approaches or prognosis models.

INTRODUCTION

Significant savings will occur through transitioning from fleet to condition-based maintenance. Common practice schedules systems for service or maintenance at pre-determined intervals (i.e.; cycles, miles, time, etc). While this is a practical way to handle fleet maintenance, it often results in unnecessary expenditures or, even worse, late maintenance of critical systems. Fleet maintenance strategies do not consider the manner in which individual systems are used. For example, fleet maintenance of aircraft assumes that all the individual aircraft are flown under similar

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Mr. Loren Nasser, VEXTEC Corporation, 116 Wilson Pike Suite 230, Brentwood, TN 37027.
Dr. Robert Tryon, VEXTEC Corporation, 116 Wilson Pike Suite 230, Brentwood, TN 37027.

operating conditions. Not considered, for example, is the fact that some aircraft are used as warfighters where others are used for training purposes. Given the conservatism built into aircraft maintenance schedules, this results in the unnecessary replacement of parts with significant useful life. For example, the Air Force estimates that greater than 95% of "good" turbine engine rotors are unnecessarily replaced. In addition to higher-than-needed spare parts expense, this unnecessarily ties up facilities and resources, and increases unavailability of equipment.

Alternatively, a condition-based maintenance approach will predict maintenance need based on an individual unit assessment. Prognosis is the fundamental technological capability that makes condition-based maintenance a near-term possibility. Prognosis combines general engineering understanding for why parts fail with state-of-awareness. As the individual system is used – its condition state is assessed – and the amount of life expended during its operation decreases its estimated remaining useful life. At some pre-determined threshold level of remaining useful life, the system is sent to maintenance for inspection or repair.

MATERIAL FATIGUE ISSUES

Structural degradation is often optimistically characterized in terms of residual strength or predicted life. Field failures sometimes derive from non-typical damage conditions. In turbine engines, for example, foreign object impacts, hot starts, or oil starvation can result in earlier than predicted failure.

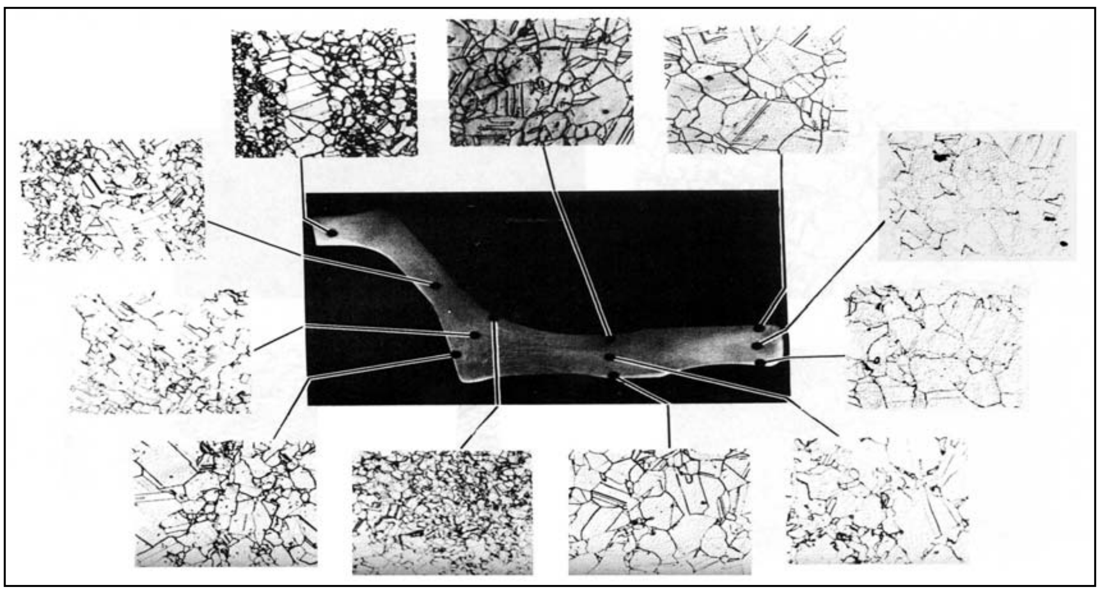

Figure 1. Waspaloy disk miscrostructure.

R&D testing limitations produces statistical uncertainty which effects life prediction accuracy for actual in-service components. Specimen fatigue life tests tend to produce a wide range of results which are generally described by the coefficient of variation (COV). The COV for annealed smooth specimens, even for well controlled, room temperature laboratory conditions, tends to vary from less than 10% to over 500% for different steel alloys. This material variability will effect prognosis accuracy, even for parts with completely known service histories.

The scatter in material behavior is attributed to the inhomogeneous microstructure arrangements characteristic within metals (or composites for that matter). Visually, metals appear to be continuous homogeneous materials; however, microscopic examination reveals a discontinuous inhomogeneous variety of individual crystalline grains, pours and defects exists. For example, Figure 1 shows a Pratt & Whitney turbine disk forging made of Waspaloy material (Cowles *et al.,* 1978). As shown, a significant amount of grain microstructural variability exists throughout the component. This typical variability is generally attributed to the metallurgical processing itself. For example, one explanation could be that the variability associated with cooling rates and forging pressures as a component is formed produces microstructural variation.

Accurate life assessment or maintenance need can be predicted through prognosis when structural material degradation - combined with future use requirements - can be approximated correctly. As already established, microstructural variability causes large scatter in the fatigue behavior of metals. Discontinuities serve as potential sites for crack nucleation. When cracks are small, they grow on the order of grain size according to the properties of the surrounding grains. As growth occurs, the rate varies until the behavior of the crack approaches bulk or average material properties.

Alloy	Test: Cyclic **Initiation (cycles)**	**Propagation (cycles)**	**Total (cycles)**	**% Initiation**
Waspaloy	19,660	7,275	26,935	73
Astroloy	117,200	2,290	119,490	98
NASA IIB-7	1,614,000	870	1,614,870	99.9
IN 100	5,888,000	2,470	5,890,470	99.6
	Test: Cyclic/Dwell			
Waspaloy	8,460	1,425	9,885	86
Astroloy	22,770	440	23,210	98
NASA IIB-7	165,600	10	165,610	~100
IN 100	63,490	125	63,615	99.8

Figure 2. Life analysis of several disk alloys.

Unfortunately traditional crack growth models do not accurately predict crack initiation or describe growth of near-grain-sized cracks. This presents a particular problem when attempting to predict failure or maintenance need. Research has shown that materials often fail before the fatigue damage reaches the long crack size because the energy associated with the damage is very high although the damage size is very small. Conventional sensing only detects large cracks (in the range of 1/32 inch).

Cowles *et al.,* (1978) performed a study that demonstrated the importance of understanding the crack initiation phase when predicting component life. A total life analysis was performed on a 2nd stage high pressure turbine disk from a Pratt and

Whitney F100 engine. This work analyzed four different nickel superalloy materials: 1) Waspaloy produced from ingot (used in the turbine section of the JT8D, JT9D, TF30, FT4 and GG8 engines and as a compressor material in the JT11 and F100 engines); 2) wrought Astroloy (produced from prealloyed powder used in the TF30 engine); 3) wrought NASA IIB-7 (produced from prealloyed powder); and 4) gatorized IN 100 (used in the F100 2nd stage turbine disk). As presented in Figure 2, study demonstrated that most of the life was spent in crack initiation. Cyclic and cyclic/dwell testing produced similar results. From the health assessment or prognosis standpoint, the goal is to identify the degradation process as early as possible in order to ensure failure prevention or timely maintenance. The P&W work illustrates the need for detecting crack development before the long crack growth stage starts. Hence, by the time traditional sensing detects a crack and long crack growth algorithms are used to predict life, failure could be imminent.

Crack Initiation

Crack initiation models are empirical in nature and don't consider the microstructural inhomogeneity discussed previously. The traditional approach models crack initiation as a simple parametric function of macro-stress and macro-strain variables. Small test specimens are cut from various component locations. The samples are cycled to a constant stress (or strain) amplitude until a load drop occurs or the specimen fractures. Although the location of specimen cuts may account for some microstructural variation, all the specimens are generally grouped together in a single test ensemble resulting in the lost of all microstructural differentiation. Conventionally, only a small amount of cyclic testing can be afforded due to both cost and time limitations. "Grouping" is therefore necessary in order to form the statistical confidence required for traditional analysis. Although the conventional approach is appropriate for determining minimum fatigue properties, it can not determine site specific properties. Also, because the models are empirical, they cannot represent any condition not specifically included in the database test program.

Traditionally used crack initiation models pose still another issue in life or failure prognosis. In service components experience mission to mission variation in applied loadings, temperature, vibration etc. Although some of this variability can be considered by combining traditional crack initiation models with cumulative damage approaches (ie Miner's rule), mission sequencing can not be accounted for. Sequencing must be considered in order to make accurate prognosis estimates. For example, a long mission followed by a short mission will cause different fatigue damage than a short mission followed by a long mission.

MICROSTRUCTURAL-BASED ANALYSIS

VEXTEC has developed a material computational testing simulation method, MICRO, that accurately evaluates the potential for component crack initiation and growth. The accuracy comes from the fact that it is a microstructual-based prediction, allowing for real-world variability, conducted as a material-specific grain by grain analysis.

MICRO effectively breaks the component down into many simple specimens – each having the microstructural properties appropriate to reflect real world conditions. The life of each individual specimen is determined and an initial component life is predicted by using system reliability estimating techniques. Using probabilistic analyses, this virtual testing process is conducted thousands or even millions of times to produce an accurate probability of failure estimate for the overall component.

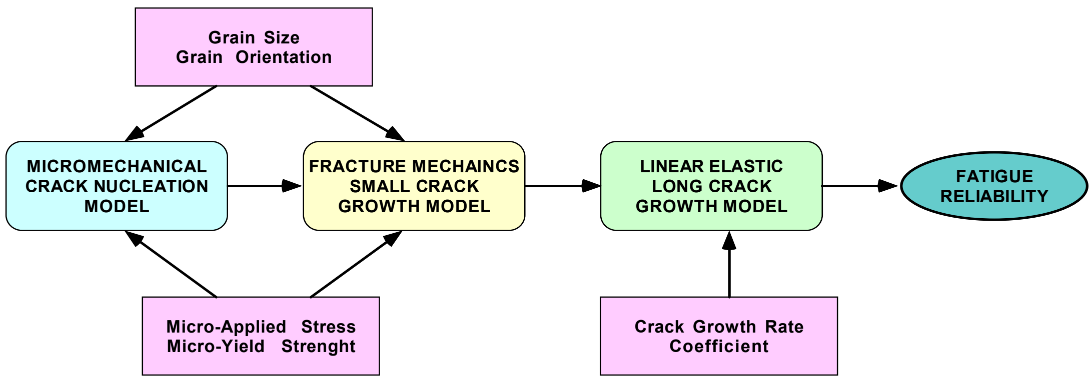

Figure 3. VEXTEC microstructural fatigue model

Figure 3 shows how MICRO evaluates each material grain through three distinct levels of accumulated damage. First, a crack nucleates on the order of the grain size. Then the crack grows as a microscopically small crack in which it lies in relatively few grains (short crack regime). Eventually the crack grows to a point where the material properties, averaged along the front of the crack, approach bulk or average material properties. At this point, standard industry long crack growth techniques are used (i.e. linear elastic fracture mechanics or company-specific models).

Real world variation in the microscopic substructure is addressed by modeling the grain size, grain orientation, micro-applied stress and micro-yield strength as random variables. VEXTEC has developed microstructural-based material behavior libraries based on the observed damage interaction with the material microstructure. For VEXTEC's work involving high strength materials, this was modeled as dislocations moving on slip planes with pinning at the grain boundaries resulting in initial defects that accommodate plastic deformation. MICRO simulated crack nucleation takes place when the accumulated dislocation exceeds the materials specific fracture energy. Thereafter the simulation may or may not grow the crack depending on the applied loading.

MICRO grows cracks through the short crack regime by emitting dislocation from the crack tips along the slip planes of the grains ahead of the short crack. The dislocation movement causes a zone of plastic deformation at the crack tip. The zone propagates freely when the crack tip is far from a grain boundary; however, as the crack tip approaches a grain boundary, the zone pins. At this point the crack may or may not grow into adjacent grains depending on the size of the plastic zone. The size of the plastic zone is dependent on the crack size, the applied load and the size, orientation and strength of the grains surrounding the plastic zone.

FAILURE PROGNOSIS

VEXTEC originally developed the MICRO approach for accurate lifing or reliability analysis through integration with commercial FEA design software. Differing from use as a design application, MICRO-based structural prognosis requires the development of a response surface to analytically model fatigue failure while accounting for condition or usage variability. The prognosis framework around the response surface model must be designed to account for 3 types of variables: sensed, referenced or inferred. Also, the framework must be analyzed through probabilistic means in order account for real world randomness.

Prognosis: Proof of Concept Feasibility

VEXTEC had access to first stage turbine helicopter wheel data which was used to demonstrate concept feasibility for MICRO prognosis. MICRO was modified to incorporate sensed, referenced and inferred variables. Monte Carlo (MC) techniques were used to realistically simulate wheel material (microstructural) variation as well as expected wheel to wheel variation in the helicopter fleet. During flight, wheel degradation could be related to burner outlet temperature (which is a conventionally sensed parameter). Since no actual sensed temperature data were available, MC was used to generate simulated onboard sensed data for the proof of feasibility work.

The demonstration project[3] simulated the flying of two separate aircraft (see Figure 4). Aircraft 1 flew a less aggressive mission profile (i.e.; trainer) and Aircraft 2 flew a more aggressive mission profile (i.e.; fighter). The probability of component failure was predicted for each mission up to the 9000th flight for both aircraft.

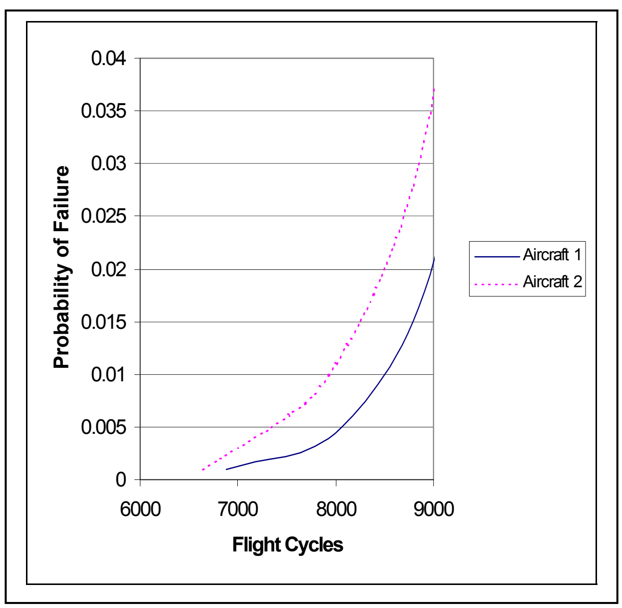

Figure 4. Predicted failure for aircraft flying different mission profiles.

The potential for prognostic-based forecast of future mission success was demonstrated by predicting expectations for missions 9,000 to 10,000 (assuming each aircraft was flown as historically had been through the 9000th mission). At the

10,000th flight, probability of mission success for Aircraft 1 and 2 was predicted to be 93.3% and 88% respectively. Also it was shown that the prognostic techniques could be used to forecast probability of mission success for an aircraft with planned change in use. The example of Aircraft 1 being used more like a fighter after the 9000th mission was evaluated. The probability of mission success (1-probability of failure) at the 10,000th flight decreased from 93.3% to 91.8% due to the plan for more aggressive flying over the next 1000 missions.

Prognosis: Ongoing Development

Upon the successful demonstration of proof of concept, full-scale development of this prognosis approach was initiated. A significant challenge that needed addressing during the development phase was the fact that each manufactured part or component will have its own unique material microstructural fingerprint (regardless of aerospace, electronic, infrastructure application). As a design application, MICRO is used to predict "fleet" life rather than life of this individual component as required for prognosis. The currently ongoing prognosis development work is focused on overcoming this challenge.

The issue can be segregated into two aspects: 1) non-destructive detection of a component's microstructurally unique fingerprint; 2) life prediction based on an individual component material fingerprint.

Techniques for material-based fingerprinting of microstructural characteristics are in development. Most of the work is focused on surface characterization (2-D) as a first step. The vision for the future is that non-destructive characterization will become a part of the conventional manufacturing process. Hence, in the future when an aircraft wheel component is made - for example - it would be automatically fingerprinted and these characterization data would be permanently associated with the part number. Technology development being funded by DARPA could yield successful non-destruction characterization capabilities within a five-year timeframe, and VEXTEC is operating under the premise this technology will be readied in parallel with it's developing MICRO prognosis software.

VEXTEC is developing the capability for life prognosis based on the input of a component's unique microstructual properties. Waspaloy, a material known to fail due to transgranular crack nucleation and defects, was selected for the current development work. The existing MICRO algorithm is being tailored for prediction of crack development and growth in Waspaloy. Laboratory cyclic fatigue testing will provide detailed and quantitative information on initiation and early crack growth (first 2-4 grain diameters) behavior in 15 micrometer grain Waspaloy at ambient temperature. About twenty specimens, rectangular bars shaped like an hour-glass on two sides with a mild curvature to localize crack initiation, will be electrolytically polished and lightly etched. Detailed information will be collected on small crack regime damage (up to 10 grain diameters) as well as on crack length, fatigue cycles and grain orientation. Atomic force microscope (AFM) will provide crack initiation information on the orientation of crack/slip bands with respect to grain boundaries.

From the optical micrographs of replicas made at different crack lengths in an initial set of specimens, it will be possible to pinpoint the approximate window of cycles at which a fatigue crack nucleates. This laboratory work will become the basis for the developed MICRO prognosis algorithm.

Blind component specimens, manufactured to simulate an in-service turbine disk, will serve as the basis for a prognosis demonstration. These specimens will represent two different microstructual arrangements. Actual component material properties will be acquired by an OEM partner and provided to VEXTEC as a simulation of sensed material "fingerprinting." The capability to accurately prognosticate failure with real-world material (microstructural) variability will be demonstrated and compared to actual cyclic fatigue test results. Also, the potential for this prognosis capability to be used within real world operating conditions will be demonstrated by conducting fatigue tests at elevated temperature (1200 F) and predicting the results.

CONCLUSIONS

Prognostic technology will eventually change the way systems of all types (ie: aircraft, land vehicles, ships, electronics) are maintained. Onboard prognostic software will be able to predict probability of failure for components or systems based on our understanding of the physics for why failure occurs. Ultimately this will serve to transition fleet-based to condition-based maintenance strategies – potentially saving millions if not billions of dollars.

VEXTEC prognosis development has focused on structural fatigue failures. It has been established that future prognosis systems of this nature must account for variability in the material behavior itself. Based on the success in proving concept feasibility, grant funding has initiated prototype development of a microstructural-based prognosis system. This effort is currently ongoing and has been linked to others developing future technology for rapid, non-destructive part (material) fingerprinting. VEXTEC will demonstrate that accurate failure prognosis is possible under real world operating conditions of temperature and part material variability.

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